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HIGH-PRECISION FE-ANALYSIS FOR SEISMIC COLLAPSE SIMULATION OF STEEL BUILDING FRAMES

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Abstract. *The project of E-Simulator is under way at Hyogo Earthquake Engineering Research Center (E-Defense), which belongs to National Research Institute for Earth Science and Disaster Prevention (NIED), Japan. E-Defense facilitates the world's largest shaking table. The E-Simulator uses the parallel EF-analysis software package called ADVENTURE-Cluster (ADVC) as a platform, and we carried out elastoplastic seismic response analysis of high-rise building frame with over 70-million DOFs. In this study, we report the results of high-precision FE-analysis for simulation of dynamic collapse behavior of the 4-story steel building frame. The whole frame is discretized into hexahedral elements with linear interpolation functions. In order to improve the accuracy of collapse simulation, a new piecewise linear combined isotropic and kinematic hardening rule is implemented for steel material, and its parameters are identified from the uniaxial material test result. The stud bolts are precisely modeled using multipoint constraints and nonlinear springs. The wire-meshes in the concrete slab are modeled using hexahedral elements. The damping due to plastic energy dissipation of exterior walls is modeled by shear springs between the floors. The accuracy of the model is verified in comparison to the physical test of steel-concrete composite beam subjected to static deformation. It will be shown that elastoplastic dynamic responses of the 4-story frame 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.*

1 INTRODUCTION

A project of Earthquake Simulator (E-Simulator) is being carried out at Hyogo Earthquake Engineering Research Center (E-Defense), which belongs to National Research Institute for Earth Science and Disaster Prevention (NIED), Japan. E-Defense facilitates the world's largest shaking table, and develops the E-Simulator, a virtual shaking table, which uses numerical computation to evaluate seismic response of structures. Advantage is taken of exclusive data that are measured in shake-table experiments. The E-Simulator will be applicable to a wide range of structures, such as steel buildings, reinforced concrete structures or ground structures.

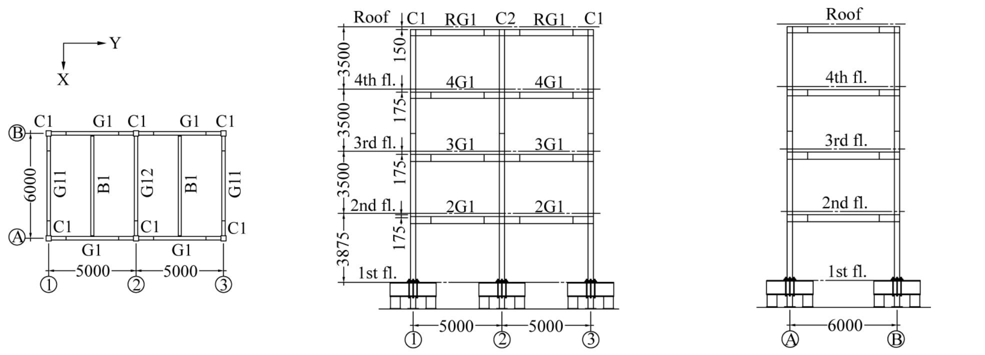
A core element of the E-Simulator is a parallel finite element (FE) analysis software package, which is called ADVENTURECluster (ADVC). ADVC is capable to be operated in a large-scale parallel computation environment; indeed, it was operated on Blue Genes in 2006 and nominated as a finalist of 2006 Gordon Bell Prizes [1], [2]. Recently, the elastoplastic seismic response analysis is carried out by using ADVC, for a detailed frame model of a high-rise building, which consists of over 70-million DOFs [3]. The detailed model is made by using solid elements, so that only constitutive relations of materials (not of structure members) are used.

It is natural to be asked whether such a massively parallel computation is needed for the estimate of seismic structure responses; a standard practice is the use of FE-analysis of fiber models. In general, FE-analysis of a fiber model is able to satisfactorily reproduce experimental data if constitutive relations of structure members are tuned up. The E-Simulator needs constitutive relations of materials instead. Even though required computation is much larger, it can reduce efforts which are made to carry out experiments needed for structure member constitutive relations.

In this study, we report E-Simulator's recent results made for dynamic collapse behavior of a four-story steel building frame. A new constitutive model is developed for steel. A detailed and precise computer model is made for key members of the buildings, by using hexahedral elements with linear interpolation function. Large-scale parallel FE-analysis using the Coarse Grid based Conjugate Gradient (CGCG) method [1], which is fast and robust parallel solver, is applied to these models.

2 PROBLEM SETTING

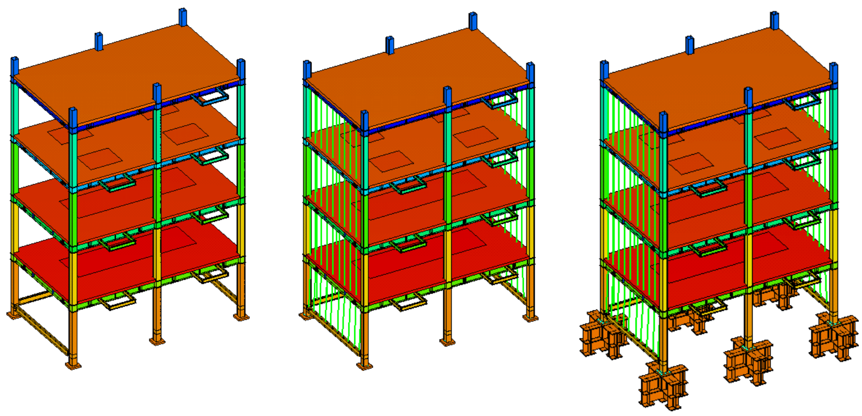
The target of the E-Simulator virtual shake-table test is a frame structure for a four-story building as shown in Fig. 1 [4]; E-Defense experiments have been made using a full-scale model of this building. The height and the floor area are 14.4 m and 60 m^2, respectively.



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

Figure 1: 4-story steel frame model [4].

FE-models for this frame are presented in Fig. 2; meshes are generated using the data and documents that have been distributed for the blind analysis contest [5], [6], and all the members as well as the floor slabs are modeled in terms of 8-node hexahedral solid elements with tri-linear shape functions. The DOFs of each node are three translational displacement components.



(a) Case A (b) Case B (c) Case C

Figure 2: FE-models of the three cases (drawn without mesh).

2.1 Steel Constitutive Relation

In order to improve the collapse simulation, a more accurate constitutive relation is used for steel. A piecewise linear hardening law with semi-implicit rules that is extended from the conventional combined isotropic and kinematic hardening law is implemented. The piecewise nature of the law has no theoretical background; it is more accurate representation of experimental observation of the hardening characteristics, that is, this law can simulate the yield plateau and the Bauschinger effect. Different rules are used for the first and subsequent loading states.

The parameters used in the piecewise linear law are determined from the cyclic uniaxial material test result. In the present law, it is set that there are six segments in which the hardening law is assumed to be linear, and eleven parameters including ratios between isotropic hardening and kinematic hardening are used to characterize each segment. The curve fitting is applied to determine these parameters, by minimizing the difference between the observed stress-strain relation and the computed one using an optimization algorithm. Figure 3 shows a typical example of the curve fitting for a cyclic uniaxial coupon test [7]. Note that a piecewise linear hardening law with seven segments is used in this example.

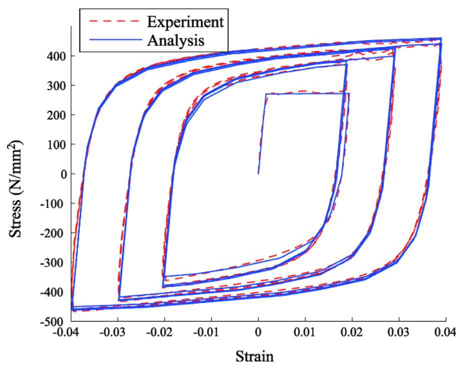


Figure 3: Parameter identification using the cyclic uniaxial coupon test [7].

2.2 Detailed and Precise Modeling

As mentioned, the E-Simulator project is aimed at developing an FE-analysis software package that uses solid elements so that the constitutive relation input is only for materials even though it results in large-scale computation. Detailed and fine meshing is needed for some structure members that have complicated configuration or complicated connection. Such detailed meshing is applied to concrete slabs and column bases as described in the followings.

While the configuration of concrete slabs of the present four-story building is relatively simple, it includes the following members that need special consideration: 1) wire meshes that are embedded in the slab to increase the stiffness; and 2) a set of stud bolts that connect the slab to beams of the floor. The wire-meshes are modeled using hexahedral elements, to evaluate accurately the reinforcement effects of the meshes; see Fig. 4. The wire-meshes are simplified, that is, the circular cross-section is changed to rectangular one and crossing reinforcements are modeled as a unified body. Figure 5 illustrates how the stud bolts are modeled. Rigid beam elements are placed at the location of the stud bolts. They are penetrated up to the second layer of the flange mesh. Note that the rigid beam should be connected to at least two nodes of the flange mesh because each node does not have rotational degree of freedom. Rigid rods are imposed to keep the distance between the beam and the slab constant. The upper end of the rigid beam is not connected to the slab, and that of the rigid rod is connected to a node of the slab mesh. The upper end of the rigid beam is connected to the upper end of the rigid rod by using the truss element. The stiffness of the truss element can be evaluated from the lateral stiffness of the stud considering the effect of the contacted concrete [8], although the lateral stiffness has not been considered for the current model yet.

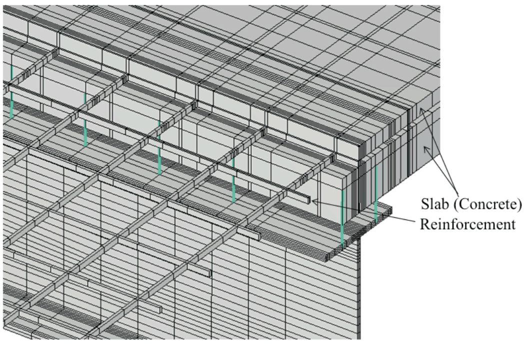


Figure 4: Composite beam.

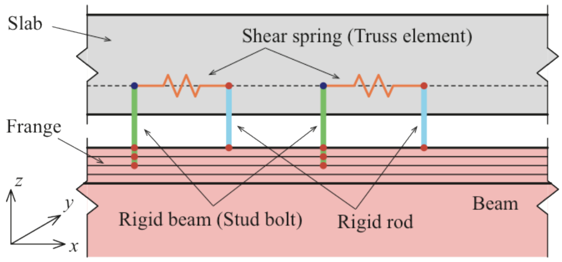


Figure 5: Modeling of stud bolt.

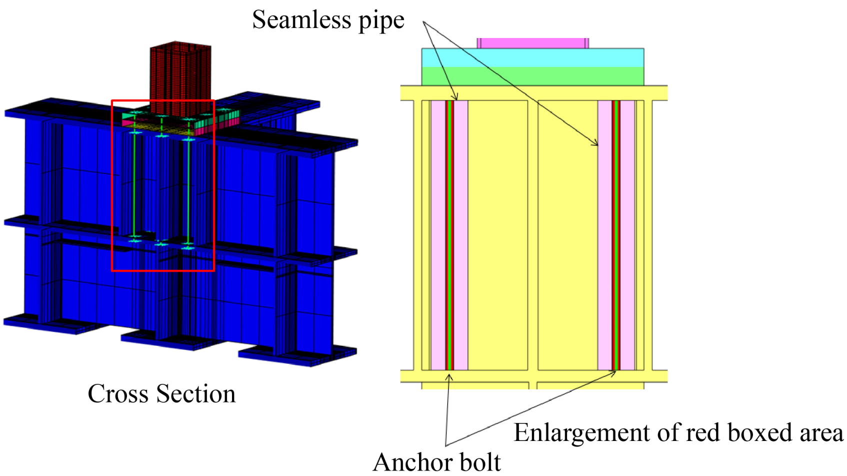


Figure 6: Column base.

Modeling of column base is illustrated in Fig. 6. The upper steel base plate and the lower mortal plate are modeled precisely. On the surface between the steel base plate and the mortar, frictionless contact condition is imposed though multipoint constraints (MPCs) are imposed for the relative displacements in horizontal X and Y directions. On the surface between the mortar and the base, the stick condition is imposed. The base plate and the base are connected by the anchor bolts that are modeled by the truss element. The base is reinforced by the seamless pipes that are also modeled by truss elements.

The extra damping of the exterior wall is due to the energy dissipation of the walls' plastic deformation. Therefore the walls are modeled by elastoplastic shear springs; see Fig. 2 (b) and (c).

Table 1: Model types.

Case	**Column base**	**Stiffness of exterior wall**	**Slab**	**Hardening law for steel**
Case A	Fixed.	Ignored.	No stud bolts, no wire-meshes	Isotropic hardening
Case B	Rotational spring based on the recommendation by Architectural Institute of Japan [9].	Shear spring (truss element) connecting the flanges of the beams in the upper and lower floors. Parameters are identified from the experimental results [10].	No stud bolts, no wire-meshes	Isotropic hardening
Case C	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.		With stud bolts and wire-meshes	Piecewise linear combined isotropic and kinematic hardening law with semi-implicit rules

3 RESULTS

In order to study the accuracy of the modeling of the column base, the slab, and the exterior wall, the three models, which are explained in Table 1, are made. Figure 2 depicts FE-models of these three cases.

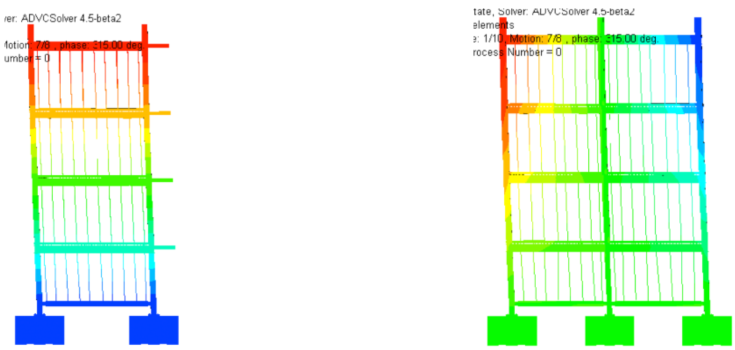
3.1 Evaluation of Natural Period

If DOFs of the analysis model is large, there is always a possibility that mistakes are made in the pre-process of the model. Natural periods and modes are first examined in the E-Simulator project, in order to find out apparent errors in the pre-process.

Assuming linear elasticity, first 6 eigen-values are computed for the stiffness matrix, from which the natural periods and the associate modes are computed. The results are summarized in Table 2 and Fig. 7. The natural periods observed in the E-Defense experiment are also included in the table. As is seen, the E-Simulator model reproduces natural periods fairly well.

Table 2: Four lowest natural periods for Cases A, B, C and experiment.

Case	Natural period			
	1st	2nd	3rd	4th
Case A	0.8389	0.8144	0.5700	0.2702
Case B	0.8303	0.8203	0.5555	0.2700
Case C	0.7836	0.7653	0.5298	0.2549
Experiment [10]	0.80	0.76	---	---



(a) 1st mode (b) 2nd mode

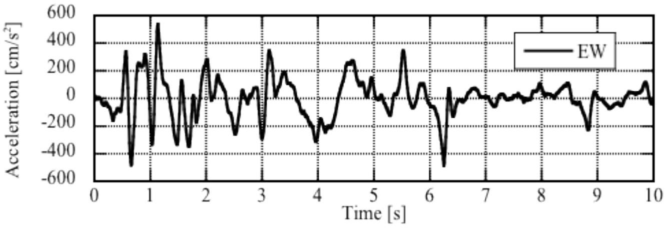
Figure 7: Two lowest eigenmodes of Case C.

3.2 Time-history Analysis for Nonlinear Collapse Behavior

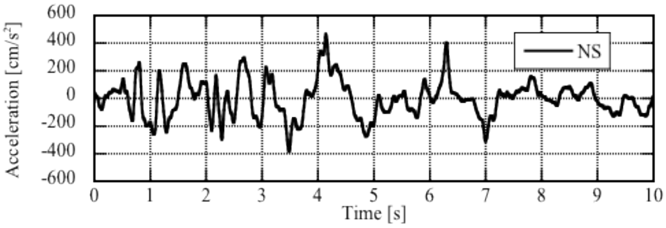
Here only the results of the time-history analyses for the two models, Cases A and B are shown. The results of Case C will be shown in the presentation. Input strong ground motions are the JR-Takatori wave of the 1995 Hyogo-ken Nanbu Earthquake; the motions are scale by 0.6. The acceleration record measured on the shaking table of the E-Defense experiment is used rather than the numerically scaled ground motion record of the earthquake; see Fig. 8, where the EW, NS, or UD direction correspond to X-, Y-, or 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 the X-direction. The Hilber-Hughes-Taylor method is employed for the time integration; the parameters are $\alpha = -0.05$, $\beta = (1 - \alpha)^2/4 = 0.275625$. A super-computer SGI Altix 4700 Intel Itanium 1.66 GHz, 1 node × 256 core, in NIED is used for computation. The computation time is 2,414 s for static analysis for self-weight, and average of 1,106 s for one step (Δt = 0.01 s) of the time-history analysis.

The time histories of inter-story drift angles and shear forces of the first story are plotted in Figs. 9 and 10, respectively. Better agreement with the experiment results is observed for Case B, than Case A. The maximum and minimum values of the inter-story drift angle are {0.01089, –0.01357} rad in the X-direction, and {0.02300, –0.007942} rad in Y-direction, whereas the experimental results are {0.0121, –0.0122} rad in X-direction, and {0.0190, –

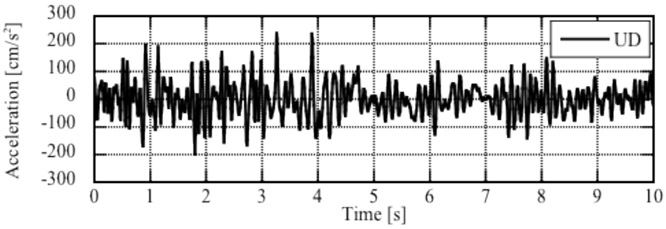
0.00933} rad in the Y-direction. Moderately accurate values are obtained by the E-Simulator. Note that residual deformation is observed only in the Y-direction. The story shear forces are calculated by the summation of the products of concentrated mass of each layer and the acceleration at the center of gravity of each layer. The maximum and minimum values of the shear forces are {1142, –1153} kN in the X-direction, and {1385, –1229} kN in the Y-direction. The measured values in the experiment are {1169, –1173} kN in the X-direction, and {1423, –1058} kN in the Y-direction. The shear forces are estimated with good accuracy.



(a) X-direction

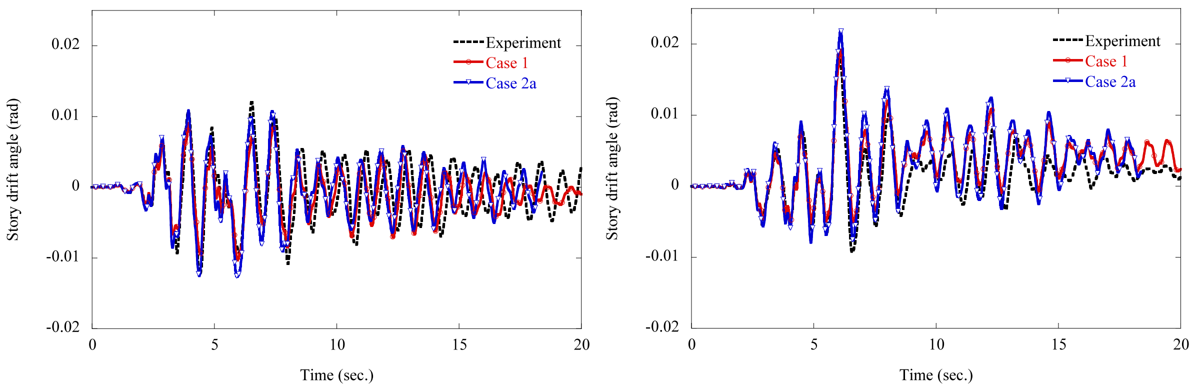


(b) Y-direction



(c) Z-direction

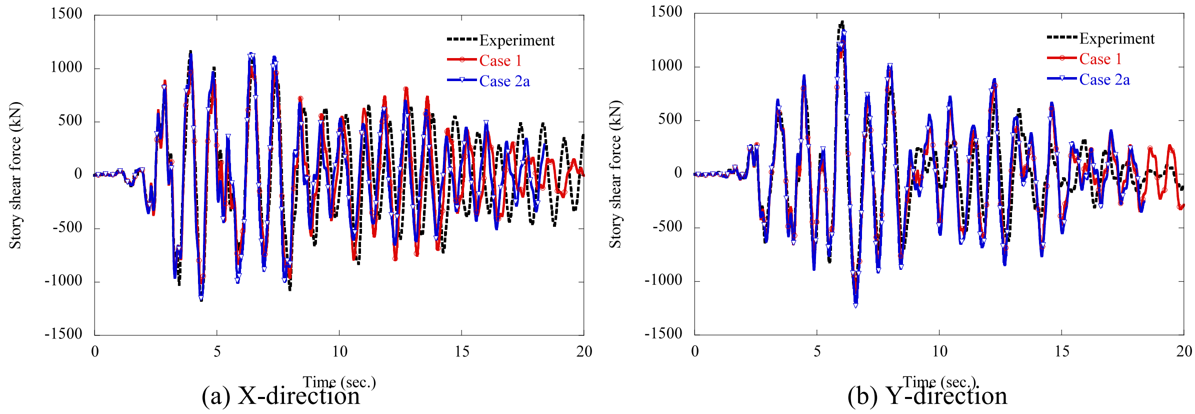
Figure 8: Input acceleration.



(a) X-direction

(b) Y-direction

Figure 9: Time-history of interstory drift angle of the 1st story.



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

Figure 10: Time-history of shear force of the 1st story.

4 CONCLUSIONS

- A virtual shake-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 shake-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 based on 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.
- The stiffness and strength of the exterior walls are modeled by elastoplastic shear springs. 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.
- The rotational spring at the column base is replaced by a precise model with hexahedral elements, multipoint constraints and truss elements. Contact between the base plate and the mortar is also considered. This model may reproduce the local behaviors such as collapse behavior at the column base.
- The effect of the wire-mesh on the stiffness of the concrete slab is considered by using a precise model of hexahedral elements. Also, the stud bolts that connect the concrete slab and the beam are modeled by the rigid beams and the truss elements. Contact between the concrete slab and the column is also considered. These modeling approaches may reproduce the behaviors of the composite beam.

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REFERENCES

[1] H. Akiba, et al., Large scale drop impact analysis of mobile phone using ADVC on Blue Gene/L, *Proc. International Conference for High Performance Computing Networking and Storage (SC06)*, Tampa, 2006.

[2] M. Ogino, R. Shioya, H. Kawai, and S. Yoshimura, Seismic response analysis of nuclear pressure vessel model with ADVENTRUE System on the Earth Simulator, *Journal of The Earth Simulator*, **2**, 41-54, 2005.

[3] M. Ohsaki, T. Miyamura, M. Kohiyama, M. Hori, H. Noguchi, H. Akiba, K. Kajiwara and T. Ine, High-precision finite element analysis of elastoplastic dynamic responses of super-highrise steel frames, *Earthquake Engineering & Structural Dynamics*, **38**, 635-654, 2009.

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

[5] M. Ohsaki, K. Kasai, Y. Matsuoka, and J. Y. Zhang, Results of recent E-Defense tests on full-scale steel buildings: Part 2 – Collapse simulation and blind analysis contest, *Proc. Structures Congress 2008*, ASCE, Vancouver, 2008.

[6] T. Hikino, M. Ohsaki, K. Kasai and M. Nakashima, Simulation of E-Defense full-scale shake-table test results of moment-resisting steel frame, *Proc. Behavior of Steel Structures in Seismic Areas*, STESSA 2009, Philadelphia, Taylor & Francis, 137-143.

[7] S. Yamada, T. Imaeda and K. Okada, Simple hysteresis model of structural steel considering the Bauschinger effect, *Journal of structural and construction engineering*, AIJ, **559**, pp. 225-232, 2002. (in Japasese)

[8] K. Yamanobe, Y. Yoshitaka, A. Wada, 2-Dimensional elasto-plastic analysis of steel frames with composite beams incorporating structural non-linearity of headed studs, *Journal of structural and construction engineering*, AIJ, **502**, 135-140, 1997. (in Japanese)

[9] Architectural Institute of Japan (AIJ), Recommendations for the Design and Fabrication of Tubular Structures in Steel, AIJ, 1990. (in Japanese)

[10] Y. Matsuoka, T. Matsumiya, K. Suita, and M. Nakashima, Test on seismic performance evaluation of exterior ALC walls with opening: E-Defense experimental projects for steel buildings – Part 14, *Summaries of technical papers of Annual Meeting Architectural Institute of Japan*, **C-1**, 1081-1082, 2007. (in Japanese)

[11] S. Yamada, K. Suita, M. Tada, K. Kasai, Y. Matsuoka and Y. Shimada, Collapse experiment on 4-story steel moment frame: Part 1 Outline of test results, *Proc. The 14th World Conference on Earthquake Engineering*, pp. S17.1.4, 2008.