High-precision FE-analysis for global and local elastoplastic responses of building frames

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ABSTRACT: Global and local responses of steel frames are simultaneously simulated using a high-precision finite element (FE) analysis considering composite beam effects. A detailed analysis is first carried out for a 4-story building frame subjected to seismic motion. The steel material is modeled using a piecewise linear isotropic-kinematic hardening that can incorporate a yield plateau. Static cyclic response analysis is then carried out for a composite beam supported by a column. 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.

1 INTRODUCTION

Global and local elastoplastic responses are simultaneously simulated for evaluating steel building frames considering composite beam effect. We use E-Simulator (Hori et al. 2007), 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-Simulator utilizes the parallel FE-analysis software package called ADVENTURECluster (Allied Engineering Corporation 2011). It has been shown that seismic responses of highrise building with more than 70 million degrees of freedom can be simulated using the E-Similator (Ohsaki et al. 2009).

A piecewise linear combined isotropic-kinematic hardening model (PLC-model) is used for the steel material. Heuristic and implicit rules are incorporated to simulate the complex elastoplastic behavior of the material under asymmetric cyclic deformation.

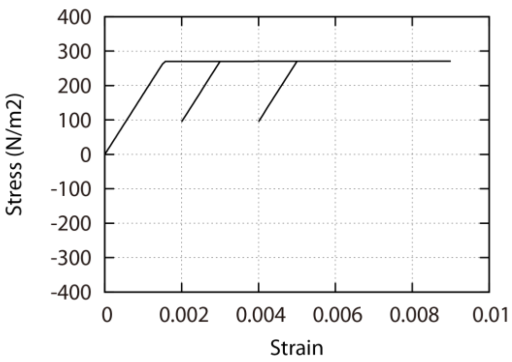
We simulate collapse behavior of a 4-story building frame, which is a specimen of the full-scale shake-table test carried out by E-Defense, to demonstrate effectiveness of high-precision FE-analysis for investigation of dynamic elastoplastic behaviors of building frames under severe seismic motions.

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 discretized into linear hexahedral elements. It is demonstrated that the experimental results, which show asymmetric behaviors due to contact of the slab to the column, can be simulated accurately by the high-precision FE-analysis using the PLC-model and a rigid beam model for the stud bolts.

2 COSTITUTIVE MODEL OF STEEL

We use the PLC-model for steel material, which can simulate a yield plateau and the Bauschinger effect (Ohsaki et al. 2011). 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 Yamada et al. (2002). 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.

Figure 1 shows the uniaxial cyclic behavior of a solid element involving unloading from the yield plateau. The yield plateau is traced after elastic unloading as shown in Figure 1a. In contrast, hardening occurs through the yield plateau, as shown in Figure 1b, if plastic loading is experienced in the opposite direction. This way, the uniaxial cyclic behavior including the Bauschinger effect and a yield plateau can be simulated accurately.



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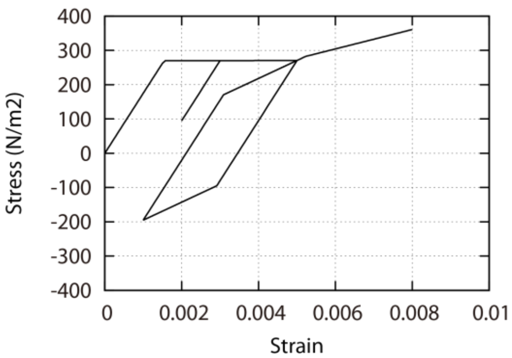

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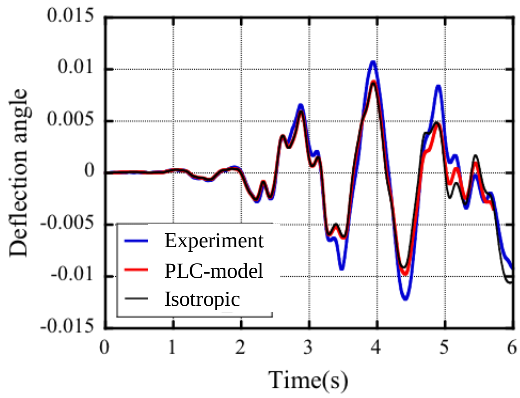
Figure 1. Cyclic behavior with reloading from a yield plateau; (a) reloading after elastic unloading, (b) reloading after plastic loading in the opposite direction.

3 SEISMIC RESPONSE ANALYSIS OF STEEL FRAME

Seismic response analysis is carried out for a steel frame, which is the specimen of the full-scale collapse test in E-Defense in 2007. See Tada et al. (2007) for details of the model. Responses under JR-Takatori wave of the 1995 Hyogo-ken Nanbu Earthquake scaled to 60% are simulated for two cases with the simple isotropic hardening model and the PLC-model. The slabs are connected rigidly to the beam flanges. The stiffness and plastic energy dissipation of the ALC panel are incorporated using shear elements between the floors, and has the bases discretized to solid elements and anchor bolts modeled by truss elements. See Kohiyama et al. (2010) for details.

The time histories of inter-story drift angles of the first story are plotted in Figure 2. As is seen, the PLC-model has slightly better agreement with the experimental result than the conventional isotropic hardening model.



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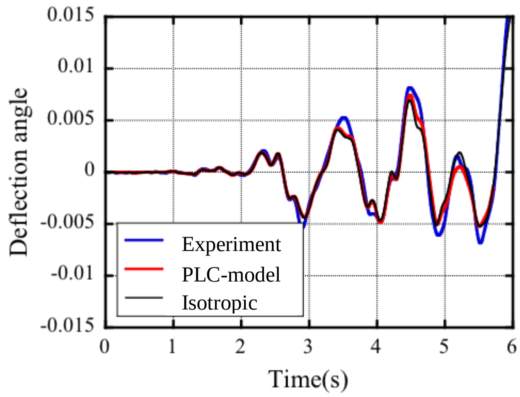

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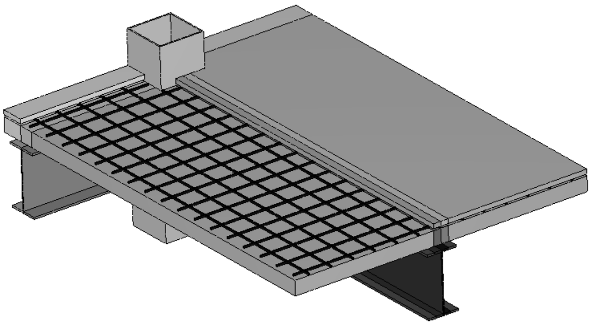
Figure 2. Time history of interstory drift angles of the 1st story; (a) X-direction, (b) Y-direction.

4 CYCLIC STATIC ANALYSIS OF COMPOSITE BEAM

4.1 *FE-model*

We next carry out cyclic static analysis for a composite cantilever supported by a column, which was investigated in Yamada et al. (2009). The CAD model and FE-meshes are shown in Figures 3a and b, respectively. The sections of a beam (girder) and a 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 PLC-model is also used here for the steel material. The hardening coefficients in initial loading are identified from the result of a tensile uniaxial coupon test as shown in Figures 4a and b for column and beam flanges, respectively. Although material parameters for a flange and a web of the beam are different, those for a flange are used also for a web. Since only the hardening coefficients for the first loading can be obtained from the tensile uniaxial test, the parameters after reloading are estimated from the properties in the cyclic test in Yamada et al. (2002).



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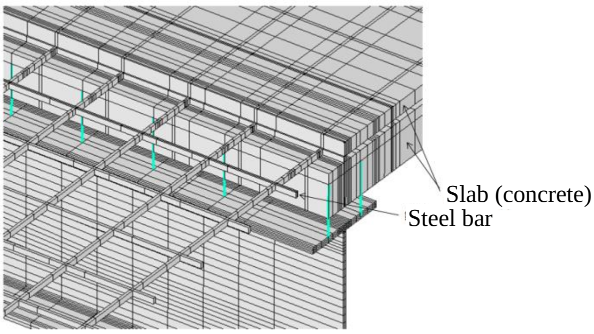

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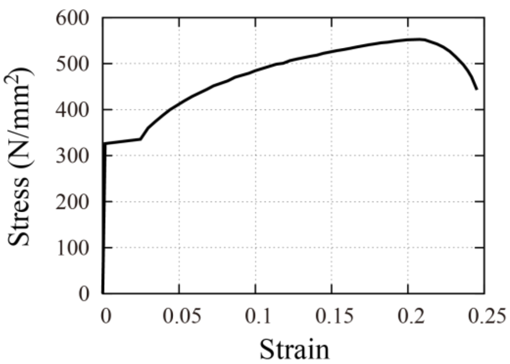
Figure 3. A composite beam supported by a column; (a) CAD model, (b) FE-mesh.



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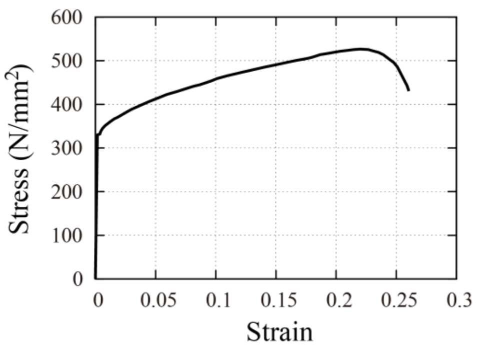
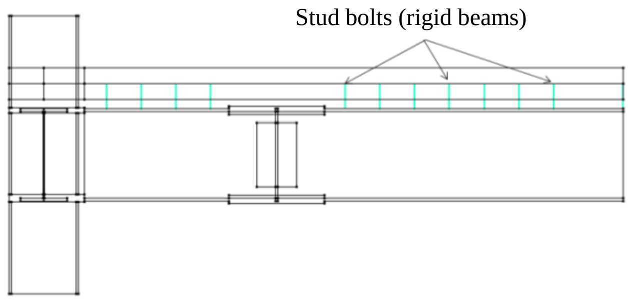


(b)

Figure 4. Relations between true stress and logarithmic strain of tensile uniaxial tests; (a) column, (b) beam flange.

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.

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 the slab, upper surface of a flange, and middle of a flange as shown in Figure 5. Note that the rigid beam should be connected to three nodes to transmit bending moment, because each node does not have a rotational degree of freedom. There is clearance between the flange and the slab, because we ignore the concrete in the level of a 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.



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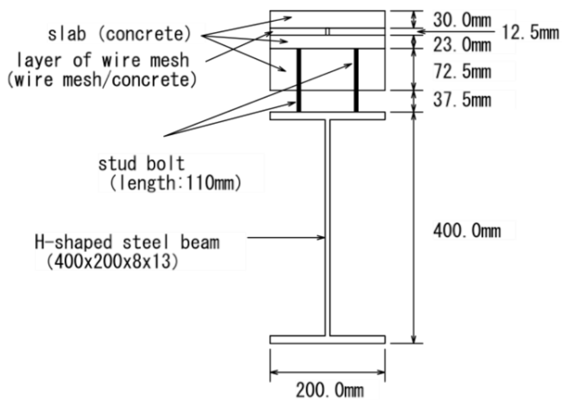

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Figure 5. Model of stud bolts; (a) elevation view: nodes of a rigid beam are connected to nodes of a slab and a flange with rigid joints. (b) section view of a girder.

The upper and lower ends of the column are supported by rigid beams that are connected to pin supports. 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 the column and the slab.

4.2 *Analysis results*

The beam is subjected to the forced rotation as shown in Figure 6, 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 Figure 7a. 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. Furthermore, the responses should be almost symmetric with respect to the rotation angle according to the loading and support conditions at a few initial cycles. However, the experimental results show moderately large asymmetry, which might have been resulted from a friction at the pin supports or deformation of the supporting frame. A good agreement is observed between the numerical and the experimental results, although the degrading property at the last cycle cannot be simulated because the softening behavior is not incorporated in the material model.

Figure 7b 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 have been estimated accurately. However, we overestimate the stiffness in the unloading state, because cracks and compressive fracture in concrete are not appropriately incorporated. Figures 8 & 9 show the distributions of the equivalent stress at the rotation angle of 0.0169 rad and –0.01733 rad in the second cycle, where the deformation is scaled by 10. The stresses in the slab near the stud bolts can be observed in both figures. Furthermore, the contact between the slab and the column is appropriately simulated at positive bending.

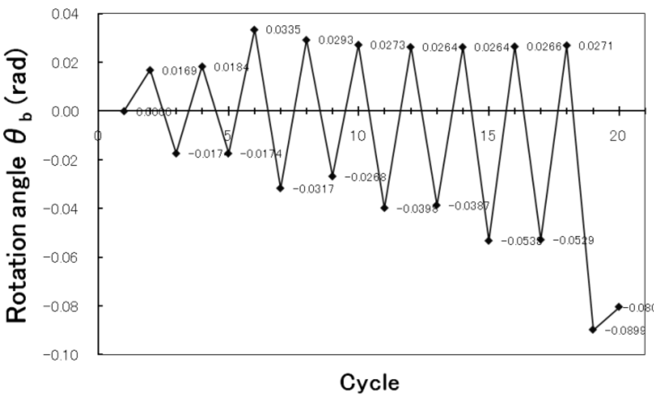
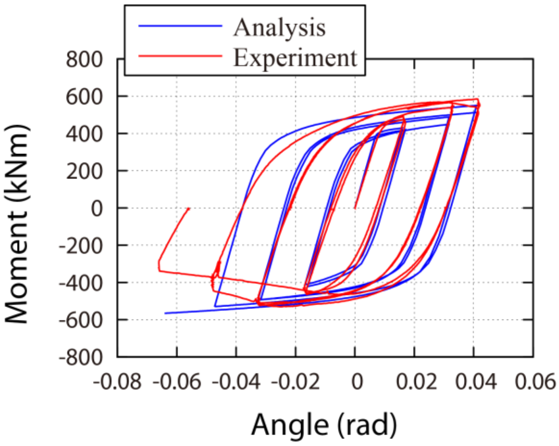


Figure 6. Forced cyclic rotation.



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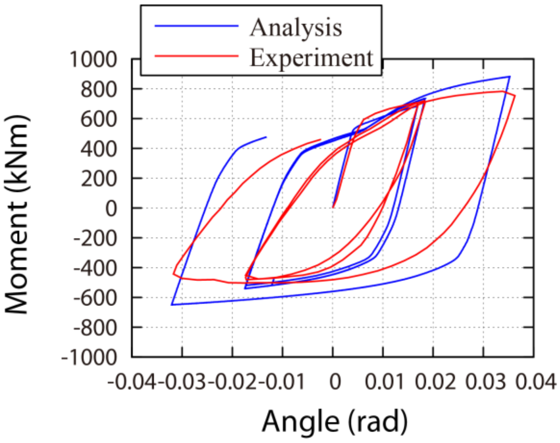

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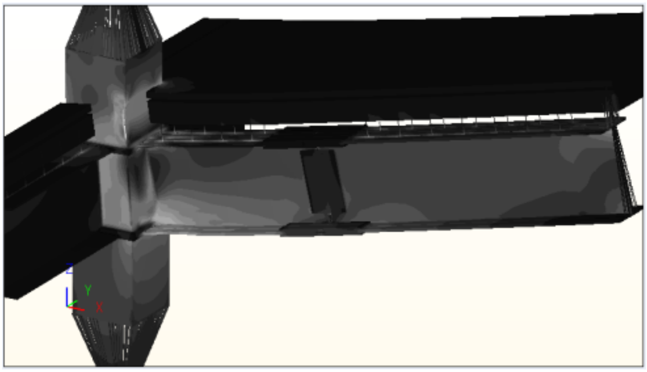
Figure 7. Relation between rotation angle and bending moment; (a) a pure steel beam, (b) a composite beam.



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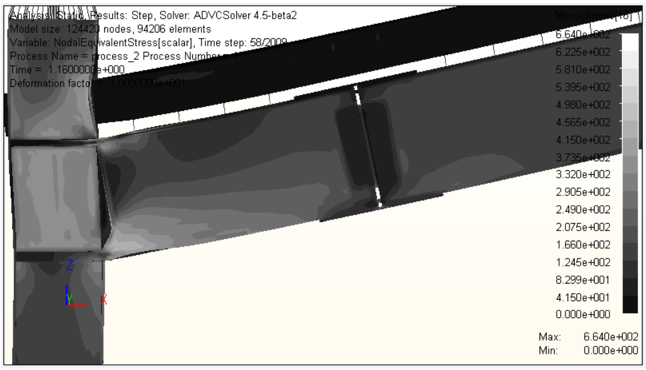

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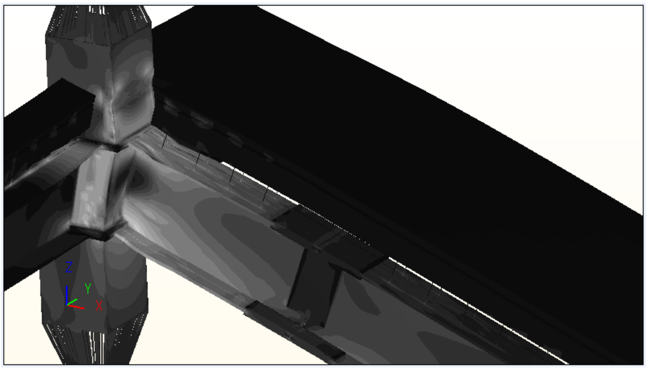
Figure 8. Equivalent stresses at rotation angle θ_b = 0.0169 rad; (a) bird's-eye view, (b) elevation view.



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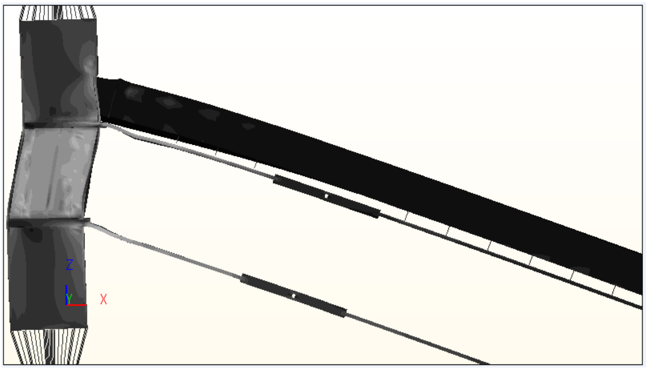

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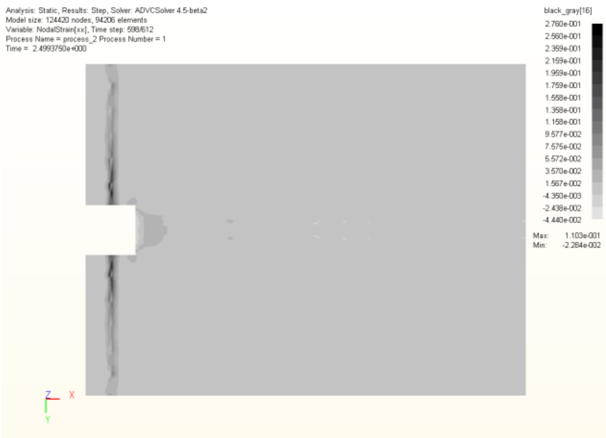
Figure 9. Equivalent stresses at rotation angle θ_b = –0.01733 rad; (a) bird's-eye view, (b) elevation view.



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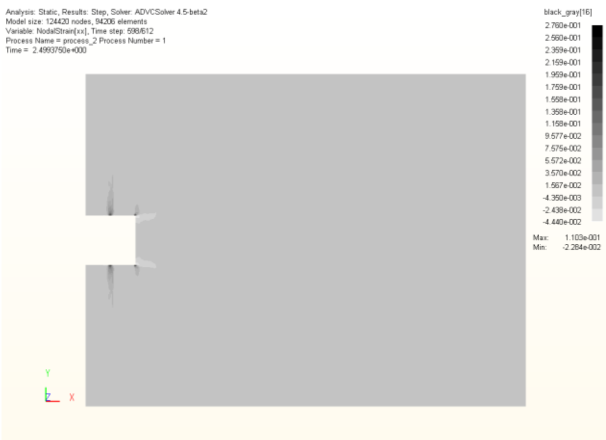
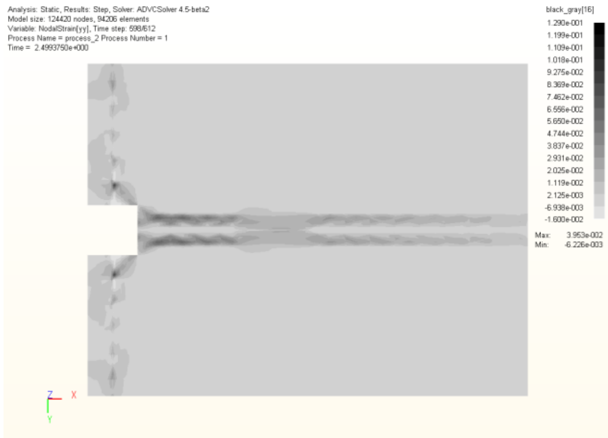


(b)

Figure 10. Strain in X-dir. at θ_b = 0.035 rad; (a) lower surface, (b) upper surface.

Figures 10 & 11 show the distributions of strain in the X (longitudinal) and Y (transverse) directions, respectively, at the angle of 0.035 rad. the large strain near the studs and the column are clearly observed. Although Yamada et al. (2009) discussed that the effect of the beams that are orthogonal to the cantilever is very small, large strain exists along the orthogonal beams.

It is interesting to note that the lower surface has larger strain in both directions than the upper surface. Large strain is observed in X direction around the studs of the orthogonal beam. In contrast, the strain in Y direction dominates near the studs of the cantilever.



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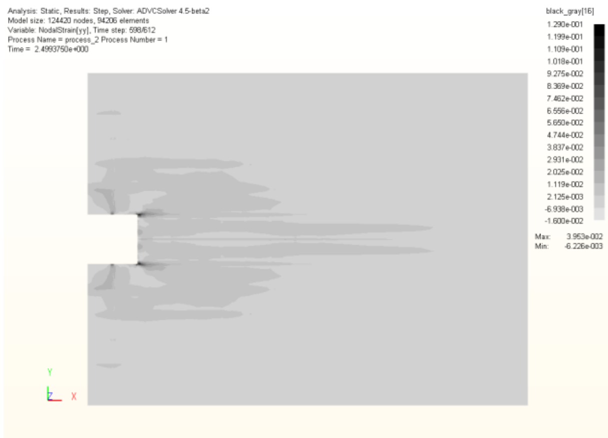

(b)

Figure 11. Strain in Y-dir. at rotation angle θ_b = 0.035 rad; (a) lower surface, (b) upper surface.

5 CONCLUSIONS

Global and local responses of a 4-story steel building frame and a composite beam have been simulated using a high-precision FE-analysis. Steel material is modeled by the PLC-model model that can simulate the Bauschinger effect and a yield plateau.

Computational results show that the strength of the composite beam under positive and negative bending states can be estimated with moderate accuracy with the extended Drucker-Prager model for concrete, rigid beams for stud bolts, and the piecewise linear combined hardening for steel, and contact condition between a slab and a column. However, cracks 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 the structural models without resort to a macro model such as plastic hinges and fiber models.

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