FINITE ELEMENT MODEL OF STEEL-CONCRETE COMPOSITE BEAM FOR HIGH-PRECISION SEISMIC RESPONSE ANALYSES OF FOUR-STORY STEEL FRAME

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SUMMARY

In this study, modeling method and numerical simulation approach are presented for high-precision FE-analysis of a steel-concrete composite beam. First, a constitutive model for steel material is improved by using piecewise linear isotropic-kinematic hardening law with heuristic and implicit rules, which was proposed by Ohsaki et al. The constitutive model is verified by using cantilever subjected to cyclic forced displacement. It is shown that the responses under asymmetric deformation can be simulated accurately using this constitutive model. Then, a detailed model of a composite beam supported by a column is constructed. The steel beam and column as well as RC-slab are discretized into linear hexahedral elements. Finally, results of the cyclic static analyses are shown. The proposed steel-concrete composite beam model will be used in the simulation of collapse behavior of a 4-story building frame, which is a specimen of the full-scale shake-table test carried out by E-Defense.

1. INTRODUCTION

The E-Simulator [Hori et al, 2007] has been developed at Hyogo Earthquake Engineering Research Center (E-Defense) of National Research Institute for Earth Science and Disaster Prevention (NIED), Japan. The purpose of E-Simulator's development is to reproduce the seismic response of building and civil structures until it reaches failure without using any macro models of structure elements. For this purpose, the E-Simulator must implement a high-precision finite element (FE) model by using solid elements, sophisticated material constitutive model and damage/failure analysis. As a platform of the E-Simulator, the parallel FE-analysis software package called ADVENTURECluster [Allied Engineering Corporation, 2011] is utilized to make massive numerical computation possible. It has been shown that the collapse behavior of a high-rise steel building with more than 70 million degrees of freedom can be simulated using ADVENTURECluster [Ohsaki, 2009].

E-Defense possesses the world's largest-capacity shaking table, which can shake a building of 1,200 tons using ground motion observed in the 1995 Great Hanshin Awaji Earthquake. Data measured in E-Defense experiments are used to validate the E-Simulator. As a target of E-Simulator, the full-scale shake table test of four-story steel frame conducted in 2007 [Suita et al, 2007] is chosen.

In this study, modeling method and numerical simulation approach are presented for high-precision FE-analysis of a steel-concrete composite beam. The proposed steel-concrete composite beam model will be used in the simulation of collapse behavior of a 4-story building frame, which is a specimen of the full-scale shake-table test carried out by E-Defense

2. CONSTITUTIVE MODEL OF STEEL [Ohsaki et al 2011]

We use a piecewise linear isotropic-kinematic hardening model for steel material proposed by Ohsaki et al. [Ohsaki et al, 2011]. The material model 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. [Yamada et al, 2002]. 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. [Yamada et al, 2002]. Figure 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. From these results, it is found that the elastoplastic responses of a cantilever under complex asymmetric loading conditions can be simulated accurately by using the constitutive model.

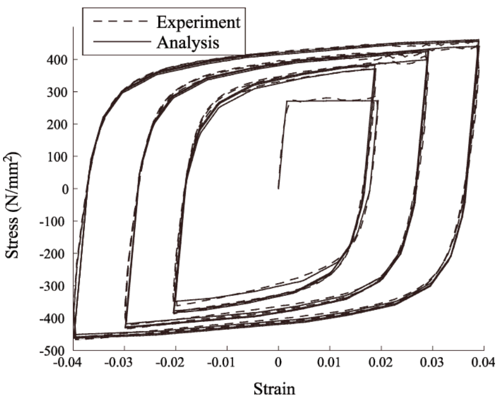


Figure 1 Verification of constitutive model of steel material

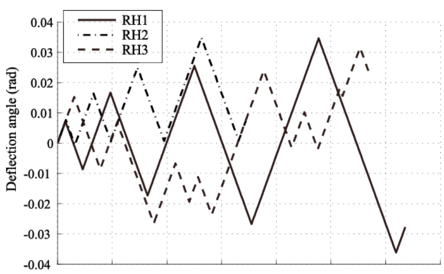
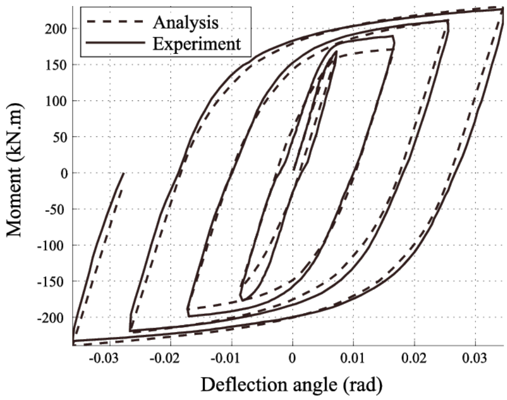
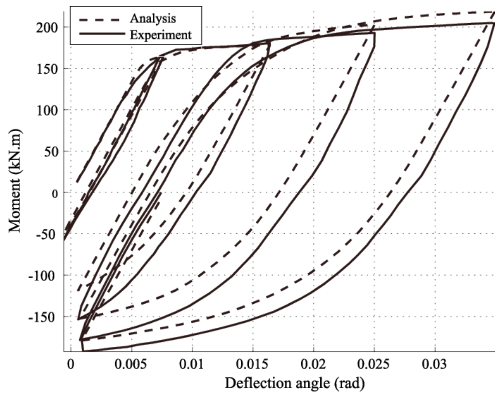


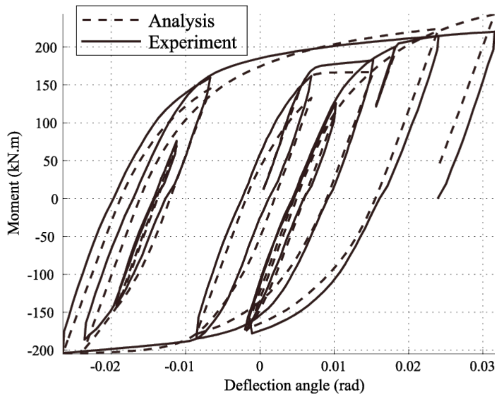
Figure 2 Three loading protocols of cantilever; RH1, RH2, RH3



(a) RH1



(b) RH2

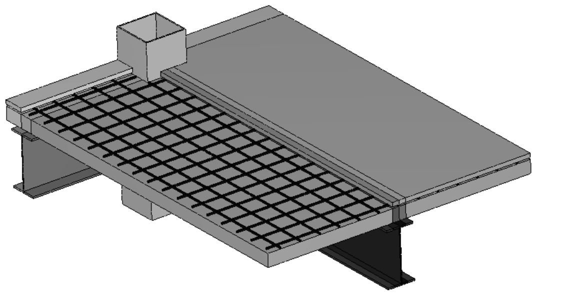


(c) RH3

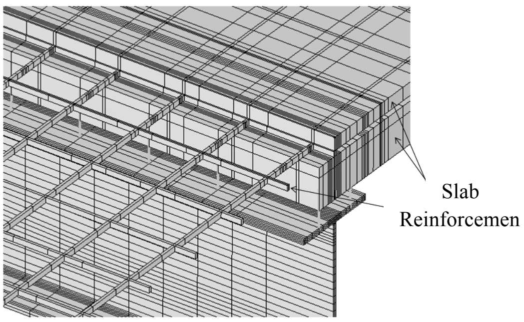
Figure 3 Relations between moment and deflection angle of cantilever

3. 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. [Yamada et al, 2009]. 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 described in the previous section is also employed here for the steel material. The hardening coefficients in initial loading are identified from the result of tensile uniaxial coupon test 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.

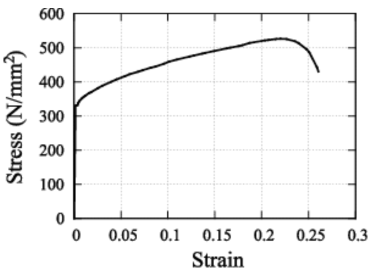


(a) CAD model

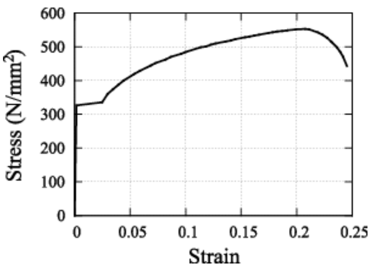


(b) FE-mesh

Figure 4 A composite beam supported by a column



(a) column



(b) beam flange

Figure 5 Relations between true stress and logarithmic strain of tensile uniaxial tests

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.

Figure 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 with 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 by experimental one, 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.

Figure 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 0.0169 and −0.0171 in the second cycle, where the deformation is scaled by 10. The effect of the stud bolts on the stresses in the slab is clearly observed near the stud bolts in both figures. On the other hand, the effect of the beams that are orthogonal to the cantilever is very small as discussed in Ref. [Yamada et al, 2009].

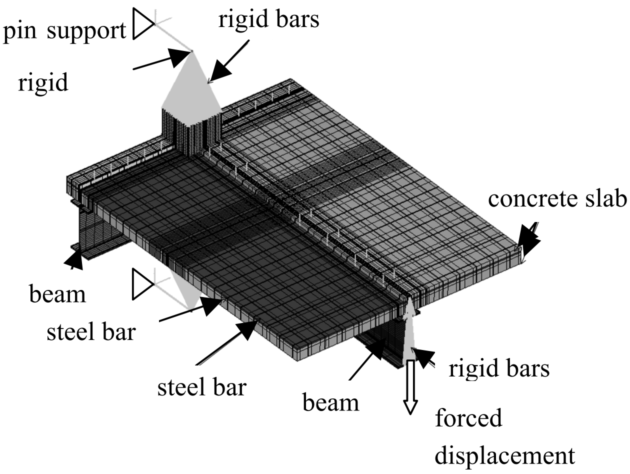
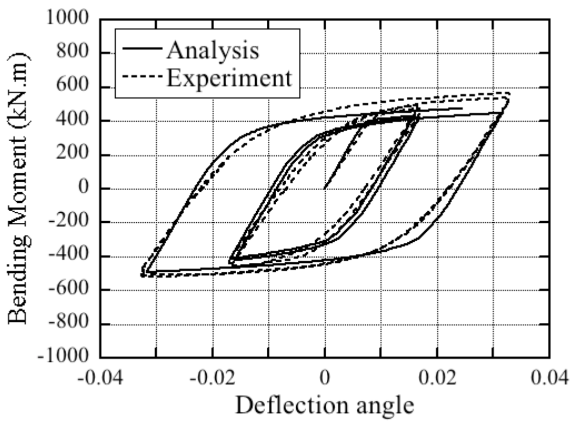
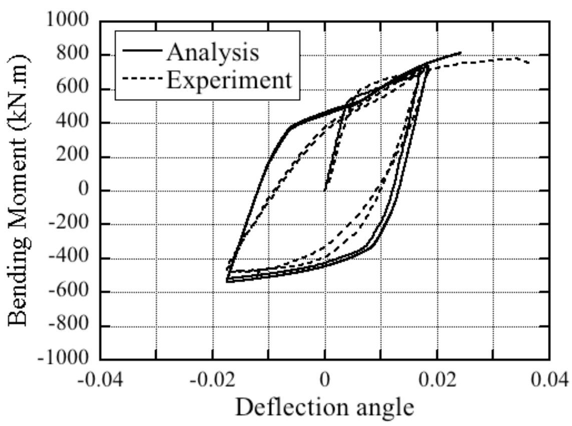


Figure 6 Support conditions of composite cantilever beam

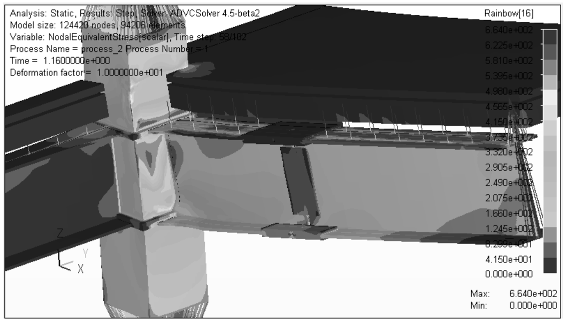


(a) steel beam

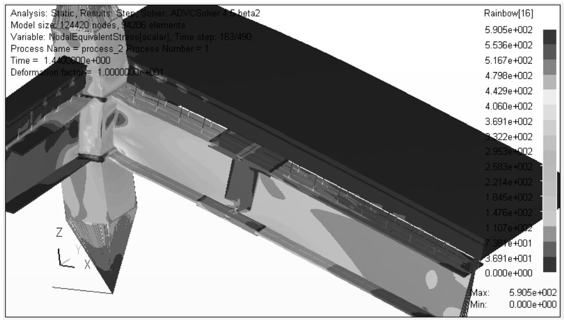


(b) composite beam

Figure 7 Relation between deflection angle and bending moment



(a) 0.0169



(b)–0.0171

Figure 8 Distributions of von Mises equivalent stress at the rotation

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 validated 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.

The proposed steel-concrete composite beam model will be used in the simulation of collapse behavior of a 4-story building frame, which is a specimen of the full-scale shake-table test carried out by E-Defense

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